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System Level Hardware-in-the-Loop Testing for Cubesats

Bryan Bingham

Cameron Weston

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SYSTEM LEVEL HARDWARE-IN-THE-LOOP TESTING FOR CUBESATS

Bryan Bingham,* Cameron Weston†

Funded by the NSF CubeSat and NASA ELaNa programs, the Dynamic Ionosphere CubeSat Experiment (DICE) mission consists of two 1.5U CubeSats which were launched into an eccentric low Earth orbit on October 28, 2011. Each identical spacecraft carries two Langmuir probes to measure ionospheric in-situ plasma densities, electric field probes to measure in-situ DC and AC electric fields, and a magnetometer to measure in-situ DC and AC magnetic fields.

During the design of DICE it was determined that a system-level hardware-in-the-loop (HWIL) test would need to be developed in order to properly test subsystem interactions with the attitude control system. The test would require simulating orbital dynamics, attitude dynamics, and environmental physics such as local magnetic fields. The flight software would need to run on a flight computer and acquire sensor measurements from real sensors which would then be used to command actuator outputs. The outputs from the actuators would need to affect the simulated attitude dynamics to perform closed loop control testing.

In August of 2010 the Space Dynamics Laboratory designed and built the Nanosat Operation Verification & Assessment (NOVA) Test Facility. The primary focus of NOVA was to provide component and system level testing for small satellites with a particular focus on CubeSats. The NOVA Test Facility was ideally positioned to provide the system level HWIL testing required by the DICE Mission. This paper will describe the design, setup, and implementation of the HWIL test performed for the DICE mission.

INTRODUCTION

The most significant advances in Earth, solar, and space physics over the next decades will originate from new observational techniques. The most promising observation technique to still be fully developed is the capability to conduct multi-point or large, distributed constellation-based observations of the Earth system at a feasible cost. This approach is required to understand the "big picture"--system-level coupling between disparate regions such as the solar-wind, magnetosphere, ionosphere, thermosphere, mesosphere, atmosphere, land, and ocean on a planetary scale. The NASA Science Mission Directorate has repeatedly identified in recent roadmaps the pressing need for multipoint scientific investigations, to be implemented via satellite constellations[1]. The NASA

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* ADCS Lead, DICE Program, Space Dynamics Lab / Utah State University, 1695 N Research Park Way, North Logan, UT 84341

† Electrical Engineer, DICE Program, Space Dynamics Lab / Utah State University, 1695 N Research Park Way, North Logan, UT 84341

Earth Science Division's "A-train," consisting of Aqua, CloudSat, CALIPSO and Aura satellites, each with different sensors, is an example of such a constellation. However, the costs to date of this and other proposed constellations have been prohibitive given previous "large satellite" architectures and the multiple launch vehicles required for implementing the constellations.

Affordable multi-spacecraft constellations can only be achieved through the use of small spacecraft that allow for much more modest fabrication, assembly, test, and launch integration infrastructures and processes as well as multiple hostings per launch vehicle. The revolution in commercial mobile and other battery powered consumer technology has allowed researchers in recent years to build and fly very small satellites, namely CubeSats. Recent CubeSat-based research initiatives, such as the NSF CubeSat Space Weather and the Air Force Space Environmental NanoSat Experiment (SENSE) programs, have spurred the development of very capable miniature space science sensors that readily integrate into a CubeSat.

MISSION OBJECTIVE

Science Research

Space weather refers to conditions in space (the Sun, solar wind, magnetosphere, ionosphere, or thermosphere) that can influence the performance and reliability of space-borne and ground-based technological systems. Ionospheric variability has a particularly dramatic effect on radio frequency (RF) systems; for example, large gradients in ionospheric electron density can impact communications, surveillance and navigation systems[2,3,4,5]. Some of the largest gradients are found on the edges of geomagnetic Storm Enhanced Density (SED) features, which regularly occur over the US in the afternoon during magnetic disturbances. The SED feature was first identified by Foster[6] using the Millstone Hill incoherent scatter radar (ISR), although Total Electron Content (TEC) enhancements caused by SEDs had been observed much earlier[6,7,8,9]. More recently, 2-D TEC maps obtained from global ground GPS receivers have shed new light on the space-time properties of mid latitude SED, and its relationship to plasmaspheric processes [10,11,12].

The formation and evolution of SED can be described by two related structures (Figure 1). The first is the formation of a greatly enhanced SED "bulge" of plasma which seems to preferentially originate at southern USA latitudes and appears correlated with storm-time prompt penetration electric fields (PPE) at low latitudes[13,14]. The second is the formation and evolution of a narrow SED "plasma plume" that first forms at the base of the SED bulge, and then extends pole-ward into and across the polar cap. The SED plume appears to be strongly correlated with the expansion of the polar convection cells, and is thought by some investigators to be due to the existence of a strong sub-auroral polarization stream (SAPS) in the local afternoon/evening mid-latitude sector [14,11,12].

Several important research questions regarding SEDs are still unanswered. First, how exactly the greatly enhanced plasma is formed over the southern USA (the SED bulge) and what is the source of the plasma. Second, exactly what physical drivers are involved in the formation and evolution of the SED plume, and what is their relative importance. Finally, the precise relationship between the occurrence of penetration electric fields (PPEs), the subsequent expansion of the Appleton anomaly crests, and the development of SED is still an open research question, particularly in terms of why there is an apparent preference for the USA geographic sector shown in figure 1. Ultimately the large redistributions of ionospheric plasma interfere with radio communications and the SED plume causes GPS navigation blackouts for users over North America. Since modern society has come to rely upon radio and more increasingly GPS, the ability to understand and predict space weather effects on these services is of importance.

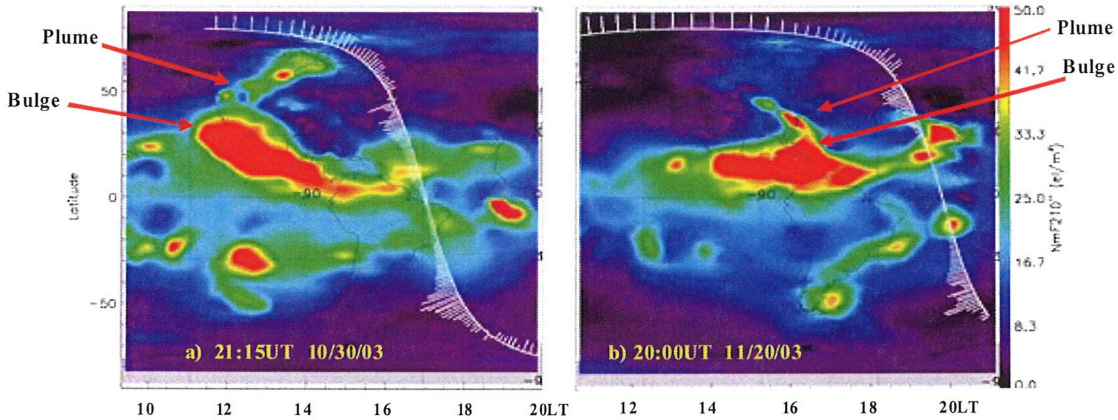


Figure 1. Horizontal distribution (Latitude vs. Local Time) of F-region peak electron density (NmF2) from IDA4D for: (a) October 30 (b) November 20, 2003. Units are $1x10^{11}$ m^{-3}. DMSP ion drift vectors shown.

To address the outstanding questions of SED science, the DICE mission has three main scientific objectives:

1. Investigate the physical processes responsible for formation of the SED bulge in the noon to post-noon sector during magnetic storms
2. Investigate the physical processes responsible for the formation of the SED plume at the base of the SED bulge and the transport of the high density SED plume across the magnetic pole
3. Investigate the relationship between PPE and the formation and evolution of SED

The DICE science objectives can be achieved via *in-situ* ionospheric electrical field and plasma density measurements from a multi-spacecraft mission. The electric field and plasma density measurements allow for the characterization of both the ionospheric plasma density and the electric field distribution. Ideally what is needed to study SEDs is a set of simultaneous co-located plasma density and electric field measurements passing through the SED bulge and plume in the afternoon sector as they start to develop and then as they evolve. Thus the DICE satellites should sample the afternoon sector between 12-16LT, where they will observe important features that have never been seen. With two spacecraft, it is possible to begin to separate temporal and spatial evolution of the SEDs. The two DICE spacecraft will drift apart in latitude over the life of the mission, so that they see the same plasma at slightly different times (time evolution).

SEDs are large-scale features; therefore high time-resolution is not required for the measurements. The electric fields causing the SED bulge and plume have similar scales. With an approximate spacecraft velocity of 7 km/sec a spacecraft will take approximately 7-14 seconds to traverse the SED plume, therefore a cadence of 0.5 to 1 seconds for the plasma and electric field measurements is sufficient to define the SED plume and the related (broader) plasma electric field structures. Although not the focus of the DICE mission, ionospheric irregularities are of great interest for space weather. Further, it has been shown that small scale irregularities form on the edges of large SED gradients[5]. The physical instability mechanism is not known, so directly measuring small scale electric fields in association with larger scale SEDs will be quite valuable. The irregularity spectrum will also be captured by the DICE mission in terms of the AC electric field spectrum measurements. In addition, observations at the Millstone Hill ISR have shown small scale electric field variability associated with the larger scale SAPS channel[15,16]. It is possible that there is a physical connection between small scale AC electric field variability and the larger scale dynamics of the SED plume development right on the edge of the large scale gradient field.

The DICE science objectives to instrument and mission performance requirements are shown in Table 1. The three science objectives for the DICE mission are listed and correspond to questions about the SED bulge and plumes, their formation and motion. **Error! Reference source not found.** also lists the minimum required measurement parameters of electric fields and density and basic instrument requirements for the investigation including the range and minimum sensitivity level for each science objective as determined by the DICE science team.

Table 1.Science to Mission Functionality Requirements Traceability Matrix

Science Objective 1: Investigate formation of the SED bulge over the USA		
Measurement Req.	**Instrument Req.**	**Mission Req.**
Measure RMS Fluctuations in Electric Field and Plasma Density: 1. Make co-located DC electric field and plasma density measurements at a ≤ 10 km on-orbit resolution 1. 2. Make AC electric field measurements at a ≤ 10 km on-orbit resolution 2. 3. Make measurements on a constellation platform of ≥ 2 spacecraft that are within 300 km	**Electric Field**: 1. Max range of ± 0.6 V/m 2. Min threshold of 0.6 mV/m 3. Min resolution of 0.15 mV/m 5. 4. DC sample rate ≥ 4 Hz 6. 5. AC sample rate ≥ 4 kHz 7. [Telemeter AC FFT power information at ≥ 1 Hz (3 points)] **Plasma (Ion) Density**: 1. Range of $2x10^{9}$-$2\ x10^{13}\ m^{-3}$ 2. Min resolution of $3\ x10^{8}\ m^{-3}$ 3. Sample rate ≥ 1 Hz	1. Constellation size ≥ 2 satellites 2. Spacecraft spin ≥ 0.8 Hz 3. Spacecraft spin axis aligned to geodetic axis to within 10 ° (1σ) 4. Spacecraft spin stabilized to within 1° (1σ) about principal spin axis 5. Spacecraft knowledge to within 1° (1σ) 5. Constellation time synch knowledge ≤ 1 s 6. Orbital insertion inclination between 55 - 98 ° (ideally sun-synchronous at 12-16LT) 7. Orbital altitude between 350 - 630 km 8. 'Circular' orbits (eccentricity of ≤ 0.2) 9. Spacecraft delV speed of ≤ 50 km/month 10. Storage/downlink ≥ 31 Mbits/day. 11. Lifetime ≥ 6 months
Science Objective 2: Investigate formation of the SED plume over the USA		
Measurement Req.	**Instrument Req.**	**Mission Req.**
Same as Science Objective 1	Same as Science Objective 1	Same as Science Objective 1 (downlink included in Objective 1)
Science Objective 3: Investigate correlation of PPE with formation and evolution of SED		
Measurement Req.	**Instrument Req.**	**Mission Req.**
Same as Science Objective 1	Same as Science Objective 1	Same as Science Objective 1 (downlink included in Objective 1)

Technology Demonstration

Perhaps the most pressing enabling technology for CubeSats is the ability to down-link large amounts of data to the ground. In addition to its science research objectives, DICE also has a major technology demonstration objective; namely to demonstrate a reliable high-speed communication downlink on non-amateur radio band from a CubeSat. This objective was identified early in the program as key to promoting and progressing the use of CubeSats, and small satellites in general, for low-cost access to space to implement multi-point measurements of the Earth system. Based on previous space flight mission experience, the DICE team determined that a CubeSat telemetry downlink capability > 1 Mbit/s would be a significant leap forward from the technology existent at the time of the DICE mission inception and would enable major research constellation missions by providing the needed bandwidth for desired measurements.

A high speed downlink requires significant spectral bandwidth and the relevant frequencies for regular non-experimental space-to-earth communications in which large bandwidths can be allocated are at UHF (460-470 MHz, 10 MHz allocation) and S-Band (2200-2290 MHz, 5 MHz allocations). The greatest difficulty in developing new communication technologies for small spacecraft is working within the regulatory framework as plumaged by the United Nations through the International Telecommunications Union (ITU) and the National Telecommunications and Information Administration (NTIA) within the United States. DICE wanted to make use of radio bands approved by the NTIA for government use in the application of space-to-earth and earth-to-space communication systems. Because the radios ultimately developed for use on DICE would be in regularly licensed bands they could then be rapidly infused into the conservative space-user community.

Broader Impact

As an NSF and NASA Educational Launch of Nanosatellites (ELaNa) sponsored CubeSat program, a key educational objective of the DICE program is that it be implemented and executed by university undergraduate and graduate students from a broad range of disciplines, under mentorship and supervision of professional staff and faculty. This objective is motivated by the desire engage, inspire, and provide training for the next generation of engineers and space scientists.

Additionally, the DICE team felt strongly that low-cost, reliable research and operational CubeSat-based missions would most readily become viable if a strong technical collaboration, based on common goals, was developed and fostered between small business, academia, government, and industry. The DICE team identified two areas which they feel are strategic to long term CubeSat mission success as well as being suitable for multi-institution partnering. Those areas, which became DICE mission teaming objectives, are:

1. Development of high-speed downlink communications for use on regularly licensed bands. This would include not only the design and implementation of a high-speed space to ground radio, but also the tools, facilities, and infrastructure to provide the ground tracking, comm link closure (i.e., high-gain ground antenna to enable the high-speed downlink), and data acquisition and management on the ground.
2. Development of miniature, reliable CubeSat deployment mechanism transducers. This refers the to the need for transducers such as wax or shape-memory alloy actuators that can operate within a CubeSat power budget and only occupy a small percentage of a CubeSat volume.

DESIGN AND IMPLEMENTATION

DICE Attitude Determination and Control Systems

ADCS on DICE is handled by both the C&DH PIC24 microcontroller and a Micromega floating point unit (FPU) on the ADCS board. Data is acquired for the ADCS algorithms via the ADCS electronics PCB, and includes 3-axis magnetometer, sun sensor vector, and GPS position and velocity measurements. The torque coil drive circuits are also located on the ADCS electronics PCB. Because the C&DH PIC24 is inefficient at calculating floating-point numbers, the FPU receives data and instructions from the PIC24, performs the calculations, and returns the results. The magnetometer and sun sensor are sampled by the data acquisition manager task every 10 Hz to feed the ADCS algorithms. The returned results are then used for pulse-width modulation firing of the torque coils.

The DICE ADCS operates in two states. The first state, Detumble, is entered upon power up of the spacecraft. The spacecraft will remain in this state permanently until commanded from the ground to do otherwise. Upon receiving command from the ground, DICE enters into its Controller state. In Detumble state, based upon magnetometer measurements the spacecraft will "slow" the X & Y axes motion (in regards to the spin rate) and begin to spin up the Z axis in preparation to operate in the Controller state where the spacecraft will maintain the desired spin rate as controlled by ground commands as well as alignment with the geodetic axis. Sun sensor and magnetometer measurements are used in the Controller state. The interaction of inputs, outputs, and ADCS algorithms for the Controller state is shown in Figure 2.

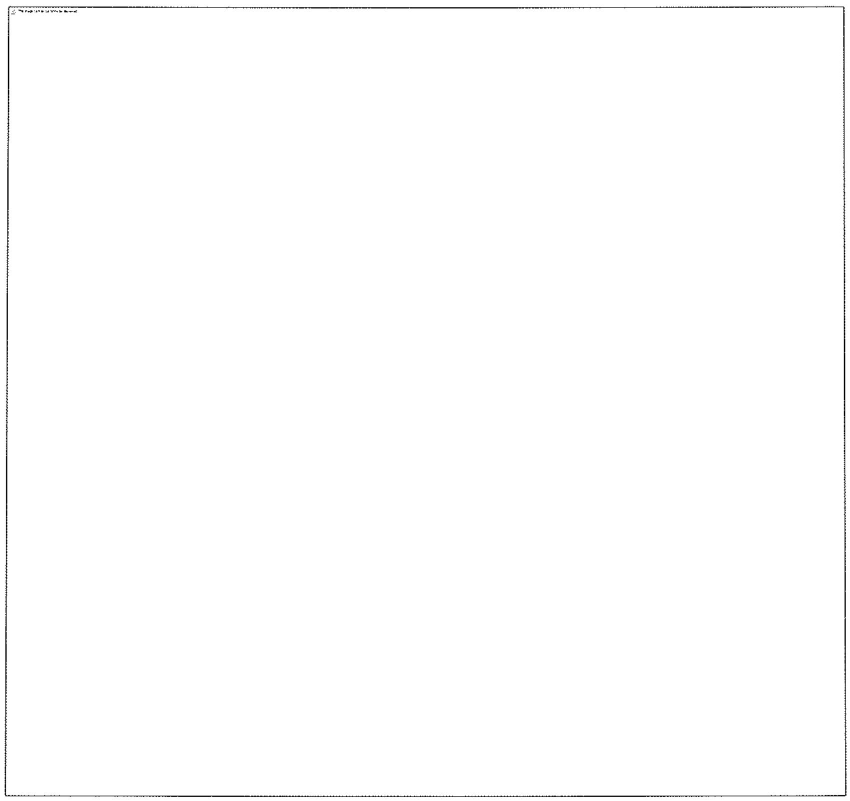


Figure 2. Data flow and events diagram for the DICE ADCS Controller state.

Each DICE spacecraft carries a NovAtel OEMV-1 GPS receiver along with a commercial L1 patch antenna placed on the +Z top place of spacecraft. As the spacecraft spins about its Z axis at up to 2Hz, the patch antenna rotates but maintains the same GPS constellation vehicles in view for several minutes allowing the receiver to acquire the signals long enough to produce a position and velocity solution. Due to the 916mW power consumption of the GPS and antenna, these devices are only powered on periodically (nominally every 3 hours) and powered down after the solution is acquired.

Pre-flight testing of the OEMV-1 using the NASA Goddard Space Flight Center GPS simulator was performed using a variety of spacecraft attitude scenarios including insertion tumbling after deployment, insertion orbit 0.1Hz and 1Hz spin with geodetic axis alignment, as well as end of life orbit 1Hz spin with geodetic axis alignment. While acquiring a consistent lock and position solution in the tumble scenario was challenging, consistent locks could be made in all other scenarios regardless of spacecraft altitude or spin rate, with time-to-lock from cold start ranging from 75 to 810 seconds and an average of 401 seconds. An interesting correlation was observed for all scenarios involving spin about the spacecraft axis which is aligned to the geodetic axis. Locks tended to acquire more quickly when cold start was initiated as the spacecraft entered low latitudes (lower than -45 degrees) as shown in Figure 3.

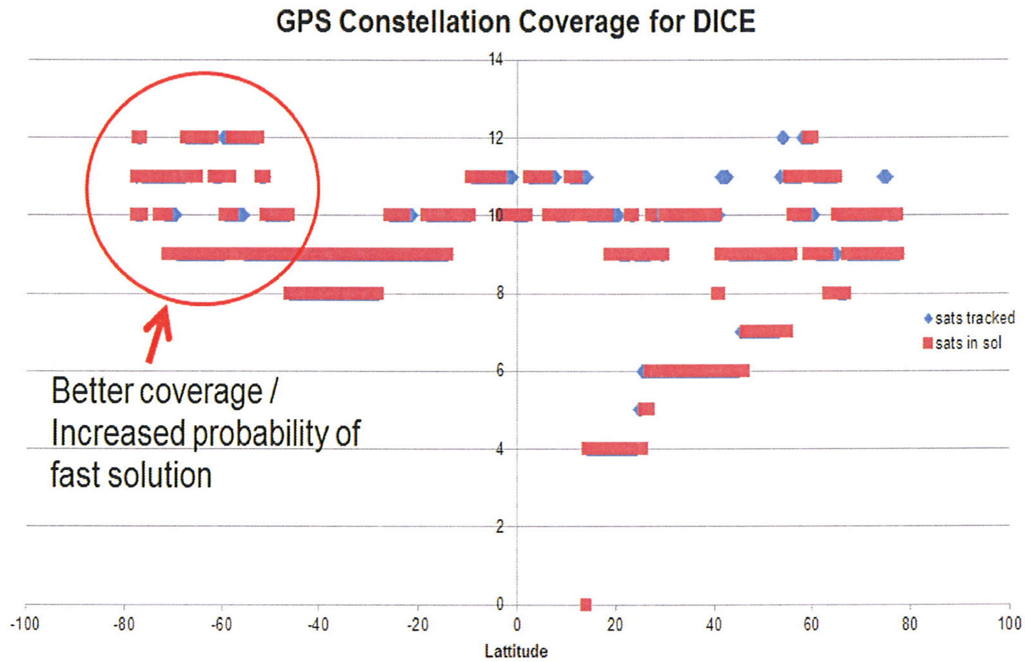


Figure 3. GPS simulation test data from NASA Goddard Space Flight Center. In this data set, the DICE spacecraft were aligned with the geodetic axis and spinning.

DICE implements a precise clock which tracks real time to < 90 ns precision in the science payload electronics FPGA. Clock drift is corrected and synchronized by the C&DH whenever the GPS receiver is powered on and producing precise time solutions, as shown in Figure 4. The time DICE time synchronization scheme allows the payload clock to be synchronized to the GPS receiver's clock to within 250 ns or within 270 ns of real time. Emulated GPS time stamps can also be sent from the ground to the spacecraft during mission operation times in which the GPS is not powered on and acquiring real GPS time, position, and velocity however, time accuracy is greatly degraded.

Hardware-in-the-Loop Testing

The DICE satellites are designed as spin stabilized satellites with their spin axis aligned with the inertial Z axis to within 30°. The DICE satellites must have a minimum spin rate of 1 Hz to deploy the electric field booms. After boom deployment, the spin rate must be maintained above 0.1 Hz for science collection. The DICE satellites have a suite of attitude determination sensors in order to accomplish the required attitude control as shown in Figure 5.

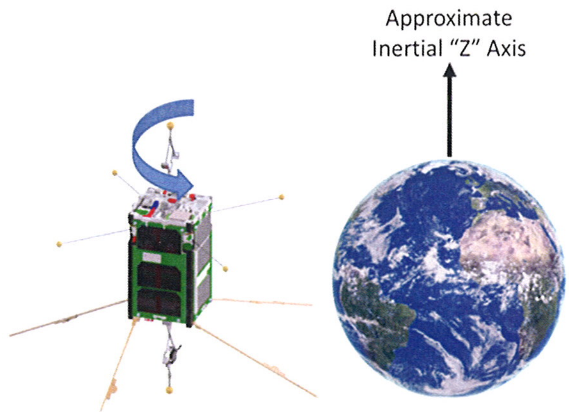


Figure 4. The DICE satellites are spin stabilized satellites aligned with the inertial Z axis.

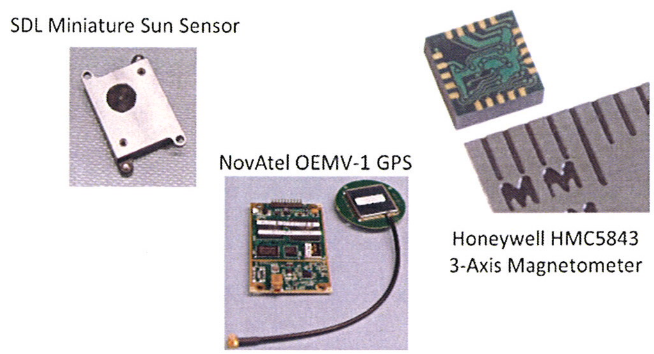


Figure 5. The DICE satellites each incorporate an SDL miniature sun sensor, a Honeywell HMC5843 3-Axis magnetometer, and a NovAtel OEMV-1 GPS receiver.

Each DICE satellite has three magnetic torque coils which are the only control actuators available. A custom wire wound torque coil was designed by SDL and is aligned with the satellite's Z axis. Two additional torque coils aligned with the X and Y axes are embedded in the solar panels designed by Clyde Space (Figure 6).

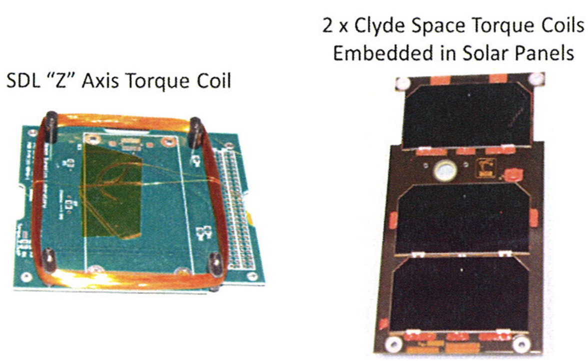


Figure 6. The control actuators for the DICE satellites are magnetic torque coils. Two magnetic torque coils are embedded in the Clyde Space solar Panels. An additional custom torque coil was designed by SDL.

In order to test the attitude determination and control algorithms a hardware-in-the-loop test needed to be implemented (Figure 7). The hardware-in-the-loop test would require running the ADCS algorithms on the flight processor. The flight processor would receive inputs from the attitude sensors and send commands to the torque coils. The output of the torque coils would affect the sensor inputs in a closed-loop manner.

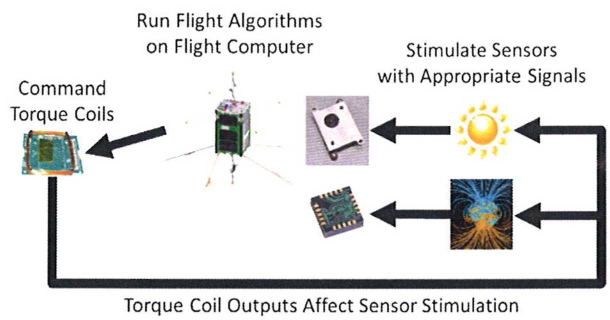


Figure 7. Design strategy for hardware-in-the-loop testing. Algorithms running on flight computer. Inputs from sensors are affected by output of actuators.

The onboard ADCS algorithms require sensors inputs that are appropriate given the current simulated date, orbital position, satellite attitude, and sensor specific stimuli (Figure 8). All of the sensors must give the appropriate stimuli or the ADCS algorithms will not be able to adequately control the satellite.

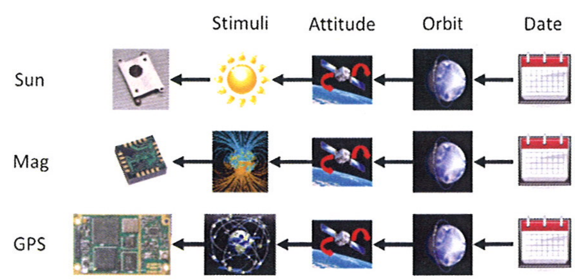


Figure 8. All of the sensor stimuli require sophisticated simulations that dynamically change given the current on orbit conditions.

The inputs to the sensors will need to dynamically change as the simulation is run. This can be accomplished in two ways: 1) The test platform containing the flight processor and sensors needs to dynamically change positions or 2) The sensors themselves must be able to dynamically change position.

In order to determine the appropriate dynamic positioning, simulations are run concurrently with the HWIL test that take into account environmental models such as solar positioning, magnetic field modeling, and gravity gradient disturbance torques on the satellites. The attitude dynamics of the satellite must also be simulated so that the current attitude of the satellite can be appropriately modeled.

In August 2010, the Space Dynamics Laboratory built the Nanosat Operation Verification & Assessment (NOVA) Laboratory. The NOVA Lab was built to facilitate the component level testing of satellite subsystems. Testing in the NOVA lab includes component level testing of the following components:

- Moment of Inertia
- Center of Mass
- Solar Array
- Sun Sensor
- Magnetometer
    - Zero Gauss Chamber
    - 3-Axis Helmholtz Cage
- Horizon Crossing (New)
- Reaction Wheels (Limited)

These individual test stations can be used to characterize individual satellite subsystems and have been of great value to SDL. Most of the test stations are unsuitable for HWIL testing, however, as they cannot be dynamically positioned.

As part of the NOVA lab, a 3-Axis closed loop controlled Helmholtz Cage was built. The Helmholtz Cage allows the creation of dynamically controllable magnetic fields. The magnetic field can be changed in real-time to simulate the magnetic fields that a satellite will experience on orbit. The Helmholtz Cage receives commands from a PC which is running Matlab/Simulink and thus is capable of running complex simulations which can be used to determine the currently required magnetic field.

Figure 9. Left: The NOVA Lab was designed by the Space Dynamics Laboratory in August of 2010 to carry out component level testing of satellite subsystems. Right: As part of the NOVA Lab a 3-axis close loop controlled Helmholtz Cage was created. The Helmholtz cage allows real-time creation of magnetic fields.

Testing the ADCS algorithms requires running the algorithms on the actual flight processor. The DICE HWIL tests were completed before the actual flight processors were completed and ready for use. The design of the DICE satellites was based on the CubeSat Dev Kit from Pumpkin Inc. and as such the Dev Kit could be used in place of the actual flight processor. The CubeSat Dev Kit was used with a PIC24 processor module which is the same processor as the DICE flight processor. The DICE ADCS Board, which includes the Honeywell magnetometer, was connected to the Dev Board (Figure 10). The Dev Board was running the same flight software making it a suitable test platform. The Dev Board is statically positioned which means the sensor stimuli must be dynamic.

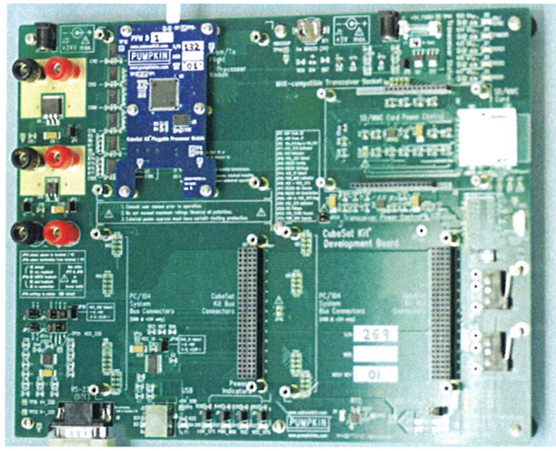


Figure 10. A CubeSat Kit Development Board was used with a PIC24 processor module and a DICE ADCS board during the HWIL testing.

During the HWIL test, the ADCS will command the torque coils to affect the attitude of the satellite. The torque coils are too weak to actually affect the attitude of the test platform in Earth's gravitational environment. The maximum torque output of the torque coils is approximately 10 μNm, which is equivalent to the gravitational disturbance torque caused by 1 gram offset by 1 mm from the center of mass. The torque coils also create a magnetic field which is being sampled by the onboard magnetometer and the feedback magnetometer in the Helmholtz Cage. If the torque coils are fired while in the Helmholtz Cage the feedback magnetometer will attempt to nullify the torque coil outputs so that their outputs are not measureable. For the HWIL test the decision was made to disconnect the torque coils and measure the voltage commands sent to the torque coils instead. Each torque coil was individually tested and a commanded voltage to magnetic moment transfer function was created. During the HWIL test the commanded voltages were sampled in Simulink and the expected magnetic moments were re-created using the previously developed transfer functions (Figure 11).

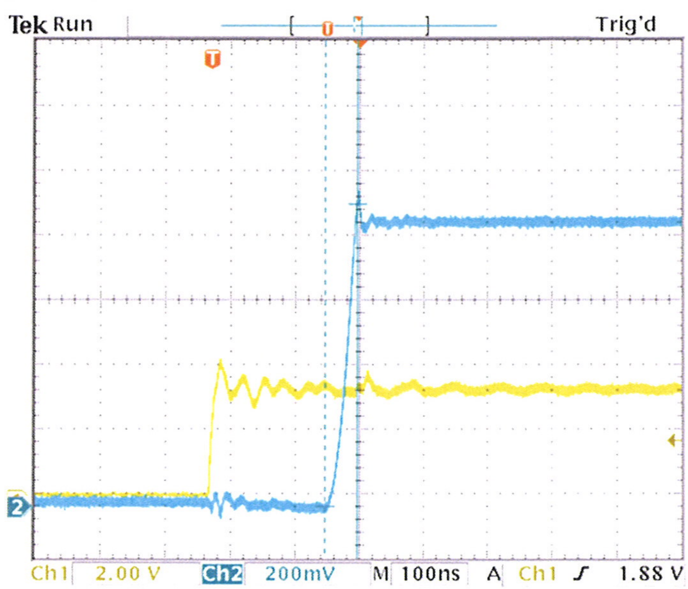


Figure 11. Each Torque Coil was individually characterized and a command voltage to magnetic moment transfer function was created.

The NOVA laboratory provides both a Solar Array simulator and a laser to test Sun Sensors. While they are useful for solar panel and sun sensor characterization they cannot be dynamically positioned which is required for the HWIL test. The decision was made remove the actual sun sensors from the test setup and instead use Simulink and knowledge of the Sun Sensors to create the voltages that we would expect the sun sensors to create and feed those to the sun sensor inputs instead. The miniature sun sensor was created by SDL and calibration equations were available to create the needed voltage to give the current solar position in relation to the sun sensor. The flight process receives the voltages and "thinks" it is receiving voltages from the sun sensors and behaves accordingly (Figure 12).

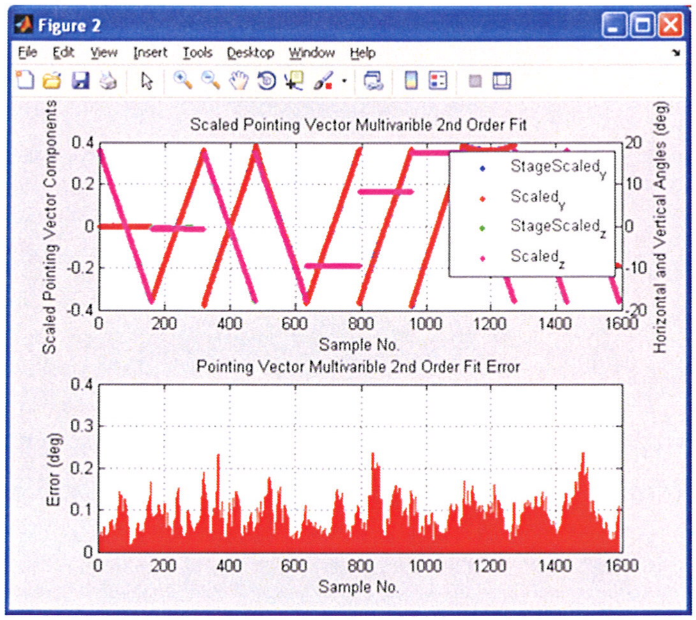


Figure 12. The sun sensor voltages could be created because detailed sensor calibration was available. These voltage inputs were fed to the Dev Board in place of voltages from the actual sensors.

Initially the OEM-V GPS receiver was going to be tested as part of the HWIL test, but the NOVA lab does not have the capability to simulate the signals from the GPS satellites. As mentioned previously in this paper the OEM-V and Antenna were individually tested using the NASA Goddard Space Flight Center GPS simulator. While this testing could not be replicated during the HWIL, GPS lock from the receiver could be "faked" by removing the GPS receiver and periodically sending correctly formatted serial messages to the flight processor. The orbital information would be generated using STK from AGI and would be accurate with the currently simulated orbital position. Due to time constraints the GPS was not simulated as part of the HWIL test. This is a perfectly valid operational mode as on orbit GPS lock may not be available for long periods of time. The onboard orbit propagator was initialized with accurate orbital data from STK, mimicking GPS, and then was allowed to drift during the test.

The final setup of the HWIL test is shown in Figures 13 and 14. The CubeSat Development Board was placed inside of the 3-Axis controlled Helmholtz Cage. The Dev Board included the PIC24 processor module and the DICE ADCS board with the Honeywell HMC5843 magnetometer. STK from AGI was used to create an accurate orbital simulation of the DICE satellites. Orbital information, Earth Magnetic Field, Solar Unit Vector, and Solar Eclipse information were fed in real-time from STK to a Matlab/Simulink Simulation. The Matlab/Simulink simulation included the attitude dynamics of the DICE satellites. Given the current attitude of the satellite and the local magnetic field, commands would be sent to the Helmholtz Cage to create this magnetic field. The expected voltages that the sun sensors would create given the current attitude and sun position were generated by Simulink and fed to the Development board. The development board would treat these voltages as from the actual sun sensors. The development board runs the actual flight software and processes inputs from the magnetometer and sun sensor inputs. It uses these sensors inputs to command the torque coils. The voltage commands created by the Dev Board are sampled by Simulink and used to create torques which affect the attitude of the satellite in the dynamic simulation.

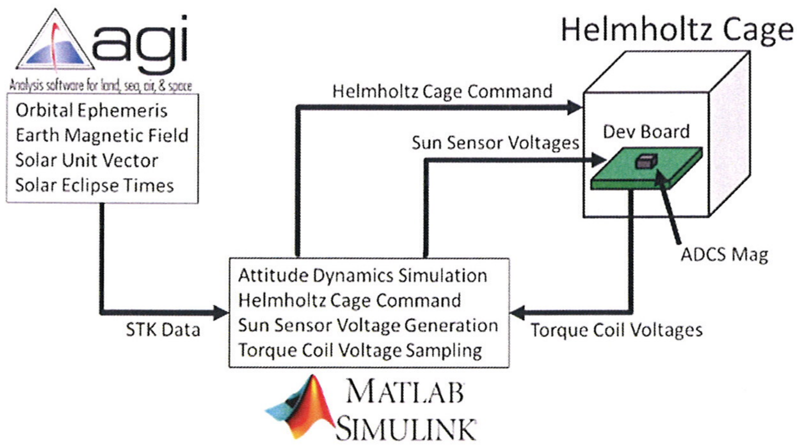


Figure 13. Overview of DICE HWIL setup. Output of actuators affects input to sensors.

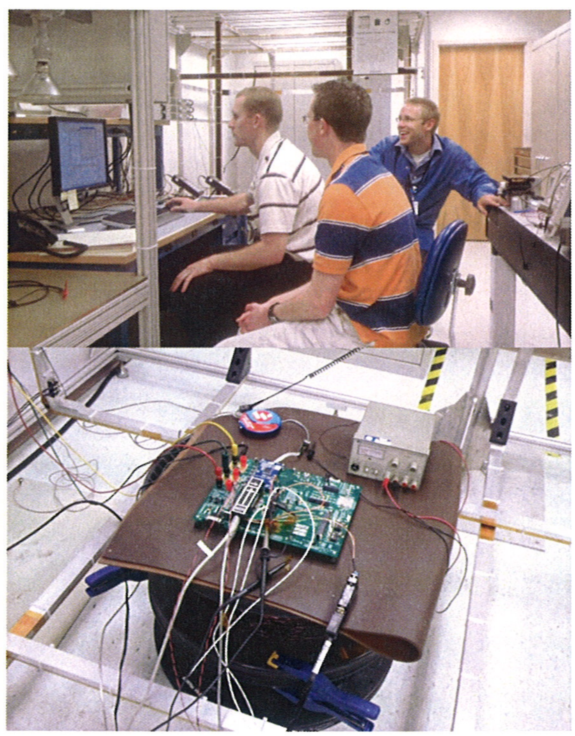
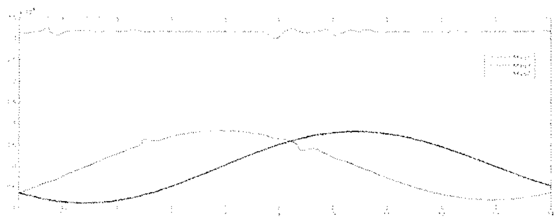


Figure 14. Actual setup of DICE HWIL Test

The HWIL test of the DICE satellites worked extremely well at verifying the ADCS algorithms. In all cases the ADCS algorithms were verified to work in a similar manner to simulated algorithms. As shown in Figure 15, the performance of the HWIL tests were "noisier" than the simulated performance, but in all cases the algorithm performance was still within requirements.

Expected Output



HWIL Output

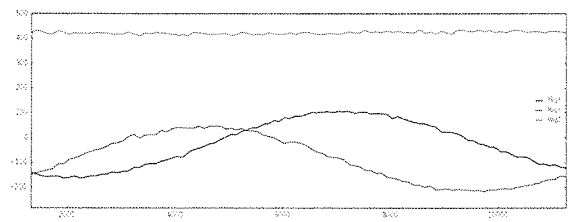


Figure 15. ADCS Algorithms performed in a similar manner as simulated algorithms during HWIL test. Performance was slightly degraded, but still within performance requirements.

Although the HWIL test worked well, there was an oversight in the ADCS design that, in the end, decreased on-orbit performance. The attitude sensor and actuator are both magnetic in nature and cannot be used at the same time. After the HWIL tests were completed and during satellite integration it was seen that the timing between sampling the magnetometer and commanding the torque coils was not working as designed. The torque coils were corrupting the magnetometer readings (Figure 16). This condition and corrective actions were investigated thoroughly in the months before launch, but it was not able to be completely mitigated before launch. The final available solution in this point in the program was to decrease the amount of time the torque coils were allowed to be on, thus increasing the amount of time available to the magnetometers to complete a clean magnetic field sample. This decrease in the torque coil on time decreased on orbit performance.

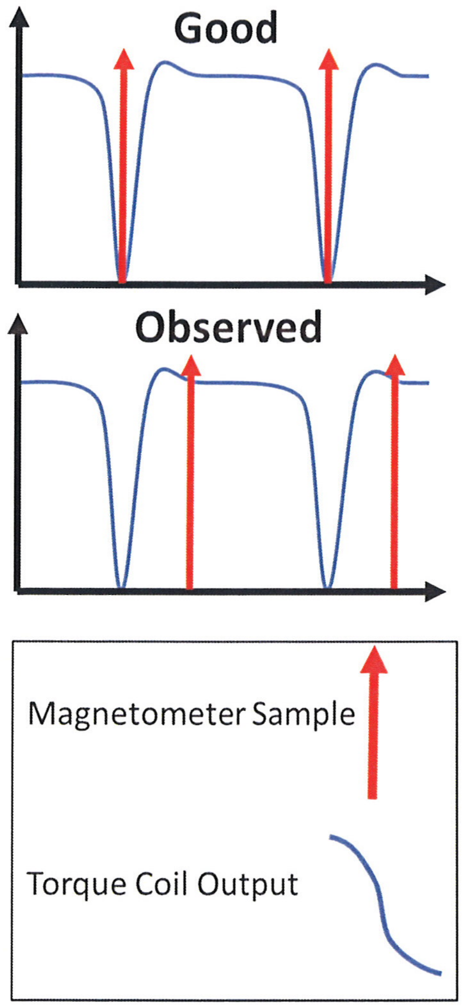


Figure 16. Timing was not tightly controlled between torque coil on time and magnetometer sampling time. This caused corruption of the magnetometer readings.

CONCLUSIONS

The ADCS algorithms for the DICE satellites were successfully tested using the NOVA Lab. The HWIL test was able to prove the algorithms by dynamically changing the inputs to the attitude sensors given the currently simulated orbital position and satellite attitude. The control outputs of the torque coils were fed into the simulation and used to affect the satellite attitude and sensor inputs.

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